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BASIC RESEARCH INVESTIGATION ON FLOW MECHANISM AND HEAT TRANSFER IN SEPARATED FLOWS

Research Grant No. NASA NsG-13-59

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I. Research Performed

A. Analytical Work

Theoretical studies conducted and progress achieved during the period covered are enumerated as follows:

1. Analytical work on components of separated flows and cavity flows has progressed as follows:

   1.1 Theoretical treatment of compressible constant pressure two-dimensional non-isoenergetic (Pr_t=1) jet mixing between two uniform streams based on integral methods. The original University of Illinois Engineering Station Report (1) has been expanded to include the Crocco Number range up to Ca^2 = .9. Information has been received that NASA has selected our report for distribution as a NASA TN.

   1.2 An abstract for a paper entitled "Constant Pressure Laminar Jet Mixing Between Two Compressible Streams with Heat Diffusion from an Initial Source" by W. L. Chow and H. H. Korst has been submitted to the Specialists Meeting of the Fluid Dynamics Panel of AGARD on Separated Flows (Brussels May 1966).

   1.3 The free streamline problem for determining transonic flow fields near sharp edged nozzle flaps has been computer-coded and limited production runs have been carried out at the University of Illinois and at Rocketdyne. This method complements the transonic flow field calculations for large radius of throat curvature fields by Sauer, or Oswatisch and Rothstein, and those developed for small radius of curvature by W. R. Seugling of Rocketdyne (2).

   1.4 Analysis of re-attaching flows has proceeded to matching of of the approaching rotational jet mixing zone with the viscous "near stagnation point" solution (see section B 1.1) of the Falkner-Skan equation (3). Present restriction to incompressible flow fields limits the usefulness of the method.

   1.5 Utilization of the flow integrals tabulated in (1) allows to formulate back-flow conditions just upstream of the pressure rise in wakes for axisymmetric base flow configurations. This allows a comprehensive treatment of problems involving axisymmetric base flow. (See section 2.5)

2. Analytical work on entire flow systems involving separated and cavity flows.

   2.1 Study of the problem of wall temperature control in cavities exposed to high enthalpy free streams.

      i) Analysis of temperature controlled mass bleeding into cavities has been expanded to cover conditions of significant boundary layer thicknesses upstream of the cavity (with the effect of finite thermal boundary layer thickness in the cavity flow presently under consideration).

ii) Extension of the analysis to include effects of non-uniform wall temperatures and controlled wall heat flux rates has been made, (see also section B. 2.) and computer code has been prepared.

2.2 Analysis of jet oscillations continued.

2.3 The wave propagation phenomenon characteristic for resonnating cavities in subsonic, transonic and supersonic flow has been studied and the representative Eiconal equation solved by numerical integration. (See section B 1.3) The results of calculations describing the configurations of the ~~acoustic~~ acoustic wave fronts emanating from resonnating cavities showed excellent agreement with that measured from Schlieren photographs.

2.4 Close coordination between work carried out under this contract and that conducted under NASA GRANT NGR-14-005-032 ("Inviscid and Viscid Interaction of Non-Isoenergetic Compressible Streams in Ejectors and Thrust Augmentation Systems") benefited both efforts tremendously. Of special importance is the information gained on the structure of initally disturbed mixing regions.

2.5 The analytical treatment of the return flow component (see section 1.5 above) has opened the way for analyizing axi-symmetric base flow problems. Quantitative results have been obtained by both long-hand calculations and by rather sophisticated computer programs. Cases treated include simple configurations, like cylinders with approaching boundary layers (with and without sting support), as well as cases of considerable complexity such as Aerospike nozzles with base bleed over large ranges of operating pressure ratios. Much of this work has been carried out in cooperation with Rocketdyne during the period of summer employment of H. H. Korst with this company. An abstract of a paper entitled "A Unified Treatment for Axisymmetric and Two-Dimensional Base Flows" by R. H. Marik and H. H. Korst has been submitted for intended presentation at the Fluid Dynamic Panel of AGARD on Separated Flows (Brussels May 1966). (Release of the material has been obtained through the sponsoring government agency at Rocketdyne and [NASA, (under NASA 8-19)]

2.6 Analysis of cavity flow, in accelerated streams has been carried out with the help of computer programs.

2.7 A new Theoretical analysis of ejector systems producing altitude simulation for unconventional nozzles has also been developed by H. H. Korst during his summer employment with Rocketdyne and the results (4) will be communicated as part of our activities under NASA GRANT NGR-14-005-032 especially in view of a supporting experimental program at the University of Illinois' extended pressure range facility. (5) (see section B.3).

B. Experimental Work

1. Experimental studies in support of theoretical work on dynamics of separated flows.

1.1 Experimental isolation of the reattaching flow field near the stagnation point of the discriminating streamline is receiving

continued attentions especially in an effort to determine the practical limits within which the process can be considered analog to the "free separation" phenomenon.

These experimental studies indicated that the base pressure will not be influenced by the modification of the wall configuration (thereby influencing the over all pressure rise), as long as these modifications are few (one to two) shear layer thickness away from the point of reattachment (either upstream or downstream or on both sides of the point of reattachment).

1.2 Low speed experiments with entire cavities have been delayed to allow structural probing of the initially disturbed mixing layer with newly acquired hot-wire anemometer equipment.

1.3 Resonance conditions were studied in more detail, especially investigating

i) the influence of varied cavity geometry on resonant frequencies (modes)
ii) the relation between wave propagation within, and external to the cavity and
iii) the interaction of such waves with shear regions and the mechanisms causing and resulting from their deformations.

These studies have been carried out mainly in the transonic blow down facility, but also by observation of pertinent features on the water table analogue. A theoretical effort will be based on a simplified physical model emerging from these studies.

1.4 Direct force balance measurements have been carried out and have so far yielded the following results:*

i) flat plate wall shear stresses show excellent agreement with data reported by other investigators (transonic regime and supersonic regime near M = 2)
ii) Systematic measurements of drag coefficients for separated flow regions (V notches) reveal the ability of the flow to such favorable low drag configurations by adjustment of the points of separation and reattachment. This phenomenon is expected to be most pronounced in the transonic regime where a form drag reduction can most effectively be achieved by such self adjustments. The different abilities of shallow, or deeper notches to perform such adjustments lead to interesting insights and suggest method for controlling the transonic and hypersonic drag of such devices as closed intakes for air augmented propulsion systems.
iii) Study of such self adjusting flows involving form drag and friction drag of comparible magnitudes leads directly to attempts to establish a theoretical model minimizing the combined drag forces.
iv) Ability to distinguish between form drag and shear drag is an important prerequisite for arriving at a meaningful theoretical interpretation of such self-adjusting flows involving separation.

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*Thesis proposal entitled "On Drag Forces of Two-Dimensional V shaped Notches in Supersonic and Transonic Compressible Flow" by R. H. Howell, Submitted to the graduate committee Chairman, Dept. of Mech. Eng., University of Illinois, Nov. 1965

1.5 Experiments with cavities in accelerated flow have started.

2. Experimental studies in support of theoretical work on thermodynamics of separated flows.

2.1 An automatic control system has been designed, constructed and is being tested, which allows to maintain individual nichrome heating strips at constant temperature.

2.2 Experiments with hot bleed air into cavities in low velocity streams are being continued.*

2.3 Heat transfer studies in high velocity flows are to be scheduled after the thermal control system in the main blow down facility becomes operational.

3. Blow down facilities operated jointly by the Department of Mechanical and Industrial Engineering and the Department of Aeronautical and Astronautical Engineering continue to be expanded. Addition of the vacuum system has extended the useful pressure ratio of the facility to 500, as established by ejector tests. Most recently, purchase of a new intensive light source DC power unit has been authorized from other main contract sources. A new interferometer system (purchased with funds from NASA NGR-14-005-032) is nearing completion.

4. Work on the continuous low-density hypervelocity facility has proceeded as follows:
   i) Bench tests conducted with the plasma torch heating unit revealed necessity for redesign of the torch-nozzle extension section to prevent leaking of the cooling system. Nozzle shape was found to be satisfactory and wall cooling provisions appeared to be adequate. Improvements in the operations-control mechanism will also be sought in the redesigned system.
   ii) The Electric hook-up of the facility has been scheduled for early November.
   iii) The entire control system, designed by General Electric Co. is to be delivered and installed by the end of October, 1965.

C. Activities

1. Publications
   i) White, R. A., "Laminar Separation and Reattachment Behind a Downstream Facing Step at Hypersonic Mach Number, Including the Effects of Approaching Boundary Layer", The Aero. Research Institute of Sweden, Report 103, Stockholm, 1965.
   ii) Korst, H. H. and Chow, W. L., "Non-Isoenergetic Turbulent ($Pr_t = 1$) Jet Mixing Between Two Compressible Streams at Constant Pressure", ME-TN-393-2, Engineering Experiment Station, University of Illinois, April 1965. (Expanded Version Oct. 1965)

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*Thesis proposal entitled "Stanton Number For Heat Transfer in Circular Cavities with Arbitrary Wall Temperature and Mass Bleed", by E. L. Bales, Submitted to the graduate Chairman, Dept. of Mech. Engineering, University of Illinois, Nov. 1965.

2. Summer activities of staff members. The departmental policy stresses the desirability of training its faculty by their participating in larger scale research activites outside our campus. This assures:

   i) contact with meaningful programs conducted in first rate facilities.
   ii) stimulation by exposure to new fields of interest.
   iii) continuous interaction between our own research work with that at other places.
   iv) gaining of technical familiarity in the operation of new equipment to be installed at the University of Illinois.

2.1 In the past summer, the following staff members participated in this off-campus phase of research.

Dr. W. L. Chow - Aerophysics Research Division, Von Karman Gas Dynamics Testing Facility, ARO, Inc. Area of Work - Hypersonic low-density flows.

Dr. H. H. Korst- Propulsion Specialist, Rocketdyne, Advanced Projects

Dr. L. Savage - Aerophysics Research Divsion, Von Karman Area of Work - Light Gas Projector Launcher.

2.2 During the absence of the project director, the activities under this contract were coordinated by Dr. R. A. White.

II. Future Plans

Continuation of analytical and experimental work as described in the main body of this report.

III. Expenditure

Expenditures incurred under NSG-13-59 up to the end of September 196[illegible] are given on page 6.

References

1. Korst, H. H., and Chow, W. L., "Non-Isoenergetic Turbulent (Pr_t=1) Jet Mixing Between Two compressible Streams at Constant Pressure", ME-TN-393-2, Engineering Experiment Station, University of Illinois, April 1965, (Expanded Version October 1965)

2. Seugling, W. R., "Program for Transonic Flow Fields in Bell and Annular Nozzles", Rocketdyne LAP 65-480(RC) August 4, 1965

3. Hayday, A. A., "An Exact Evaluation of the Effect of Uniform Free Stream Vorticity on Certain Laminar Flows of Boundary Layer Type," Department of Mechanical Engineering, University of Illinois, unpublished note, Aug., 1962.

4. Korst, H. H., and Schmurstein, R. E., "Theoretical Determination of Performance Characteristics for Ejector Systems Designed to Accommodate Unconventional Nozzles for Altitude Simulation Testing, (U), Rocketdyne LAP 65-525 (RC) August 20, 1965.

5. Korst, H. H., "Experimental Investigation of Truncated Shrouded Spike Nozzle-Ejector Systems at the University of Illinois Blow-Down Facility (U)," Rocketdyne LAP 65-519 (RC), August 19, 1965.